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The purpose of this investigation was to determine the effect of systematic changes in hip position/configuration on cycling peak anaerobic power (AP) and anaerobic capacity (AC). Fourteen male recreational cyclists (ages 21–32 yrs) were tested in four hip positions (25, 50, 75, and 100°), as defined by the angle formed by the seat tube and a vertical line. Rotating the seat to maintain a backrest perpendicular to the ground induced a systematic decrease in hip angle from the 25 to the 100° position. The Wingate anaerobic cycling test was used on a Monark cycle ergometer with a resistance of 85 gm/kg of the subject's body mass. Repeated-measures MANOVAs and post hoc tests revealed that AP and AC in the 75° hip position were significantly greater than in the 25 or 100° position and that a second-order function best describes the trend in AP and AC with changes in hip position.

In the 1930s, Francois Faure, a relatively unknown racing cyclist, defeated the world champion, Lemoire, in a 4-km pursuit race. What was unique about this feat was that Faure used a supine recumbent bicycle and broke track records that had been established on conventional bicycles. In 1980 the single rider Vector tricycle established a new human powered speed record at 56.66 mph (91.19 km/hr) with the cyclist in a supine recumbent position. This would suggest that recumbent bicycles are faster than conventional ones.

It is well documented that recumbent human power vehicles are more effective aerodynamically than the standard cycling position (Kyle, 1974, 1982; Kyle & Caiozzo, 1986; Kyle, Crawford, & Nadeau, 1973, 1974; Whitt & Wilson, 1982). With speeds of some human powered vehicles exceeding 60 mph (96.6 km/hr) (Gross, Kyle, & Malewicki, 1983), the importance of minimizing aerodynamic drag is obvious. But when the drag coefficient and effective frontal area have been reduced to 0.11 and 0.5 sq. ft, respectively, as in the Vector Single (compared to 1.1 and 6.0 sq. ft, respectively, for a standard upright bicycle) (Gross et al., 1983), it is questionable as to (a) how much lower the aerodynamic drag can be reduced, and (b) how significant such changes would be.

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The design of human powered vehicles has focused exclusively on the aerodynamic properties of the vehicle with the cyclist. To further improve performance, it becomes necessary to focus on some aspect other than the aerodynamic properties. The most logical area to explore would be the human "engine" that powers the vehicle. How an individual should be seated, configured, orientated, and/or positioned to maximize power production and cycling performance in a human powered vehicle is unknown.

Position is defined by the location of the cyclist's hip relative to the pedal axle of the bicycle and is determined by the angle of the bicycle seat tube and a vertical line (perpendicular to the ground) passing through the pedal axle. Configuration is defined by the angles of the different body segments (hip, knee, ankle) relative to each other. Orientation is defined by the angle of the cyclist's trunk relative to the ground.

To date, no scientific investigations have systematically examined the positions, configurations, and orientations a cyclist should adopt to maximize power production and cycling performance. There has not been any logical rationale or empirical evidence as to why one position, configuration, or orientation should result in greater power production and cycling performance than another, or why a cyclist should adopt a recumbent position except to minimize aerodynamic drag. This area is largely unexplored and in great need of research if the limits of performance in human powered vehicles are to be achieved.

Although cycling is generally an aerobic task, there is a need to investigate anaerobic cycling performance if new human-powered speed records are to be attained. Such records are determined over a 200-meter timing trap. The Vector Tandem, a two-person vehicle, established a speed record of 62.92 mph (101.3 km/hr) in 1980 (Gross et al., 1983). (The current world record is 105.36 km/hr set in 1986.) The task was accomplished in approximately 7.1 seconds and this is primarily anaerobic in nature.

This would suggest that anaerobic power and capacity are important variables to consider in conjunction with how changes in position, configuration, and orientation affect power production and cycling performance. It should be noted that the most effective position, configuration, and orientation may not necessarily minimize aerodynamic drag. The optimum seating position may involve some compromise between minimizing aerodynamic drag and maximizing cycling effectiveness.

Therefore the purpose of this investigation was to determine the effects of systematic changes in hip position/configuration, while maintaining an upright trunk orientation, on cycling peak anaerobic power and anaerobic capacity.

Methods

Subjects and Apparatus

Fourteen healthy males between 21 and 32 years of age (mean = 26.2 years) volunteered to participate in this study. Their average height and mass were 1.75 m (*SD* = 0.04) and 69.8 kg (*SD* = 6.2), respectively. The subjects were students with ordinary daily and recreational cycling experience.

To accommodate the changes in hip position and configuration, a variable-position seating apparatus was interfaced with a Monark bicycle ergometer, allowing for manipulations with 3° of freedom. These included changes in seat tube angle, changes in seat backrest angles, and changes in seat-to-pedal distance. For each hip position, the seat-to-pedal distance was adjusted to remain 100% (to within 3/4 in. or 1.905 cm) of the total leg length, as measured from the greater trochanter of the femur of the right leg to the ground.

Procedures

Five test sessions were required of each subject. The first session was used to obtain informed consent and anthropometric measurements and to familiarize each subject with the apparatus and test protocol. Each of the remaining four sessions was used to test a different hip position/configuration. The hip position was defined by the angle formed between the seat tube and a vertical line. The four hip positions as defined by this angle were 25, 50, 75, and 100°. For each position, the hip configuration was defined by the average hip angle for one complete pedal revolution (average differences between minimum and maximum hip angle). By rotating the seat to maintain a backrest perpendicular to the ground, a systematic decrease in hip angle from the 25 to the 100° position was induced (Figure 1).

All subjects were tested in each hip position with the testing sequence randomly determined. There was a minimum of 24 hours between test sessions. For each position, the subject was strapped to the seating apparatus at the hip and at the trunk. Pedal toe-clips were worn and used for all test sessions. In each position, the minimum and maximum hip, knee, and ankle angles were measured with a goniometer for one complete pedal revolution. The test protocol used was the Wingate anaerobic cycling test (Lamb, 1984). This consisted of a warm-up during which the subject cycled 2 to 4 minutes at an intensity sufficient to elicit a heart rate of 150–160 bpm.

The cycling was interspersed with two to three all-out bursts of cycling of 4–8 seconds each. A 3- to 5-min rest interval followed the warm-up just before the test began. To begin the test, on command, the subject pedaled as fast as possible. Simultaneously, the resistance was increased to 85 gm/kg of the subject's body mass (5.0 joules/pedal rev/kg BM). The subject then pedaled as fast as possible for 30 seconds. After completion of the test, the resistance was reduced and the subject was encouraged to continue pedaling at a light load for 2 to 3 minutes to facilitate recovery.

During the test, a microswitch in conjunction with a Technirite analog strip recorder was used to monitor ergometer flywheel revolutions. The recording paper had 10 squares/cm and the recorder speed was set at 25 mm/sec. This allowed a measurement resolution of 0.5 flywheel revolution during unloaded pedaling at maximum speed.

Peak anaerobic power was determined by the largest number of flywheel revolutions recorded during any successive 5-sec interval during the 30-sec test. Because the pedal resistance was determined according to each subject's body mass, the recorded number of flywheel revolutions represented peak anaerobic power normalized according to body mass. Normalization of peak power allows for comparison with other investigations. This relative peak power was calculated by the following equation: Power (kgm/min) = distance traveled by one flywheel revolution (6 m per revolution) × flywheel resistance (kg) × pedaling frequency (rpm).

Because one watt equals 6.12 kpm/min (Astrand & Rodahl, 1977), the

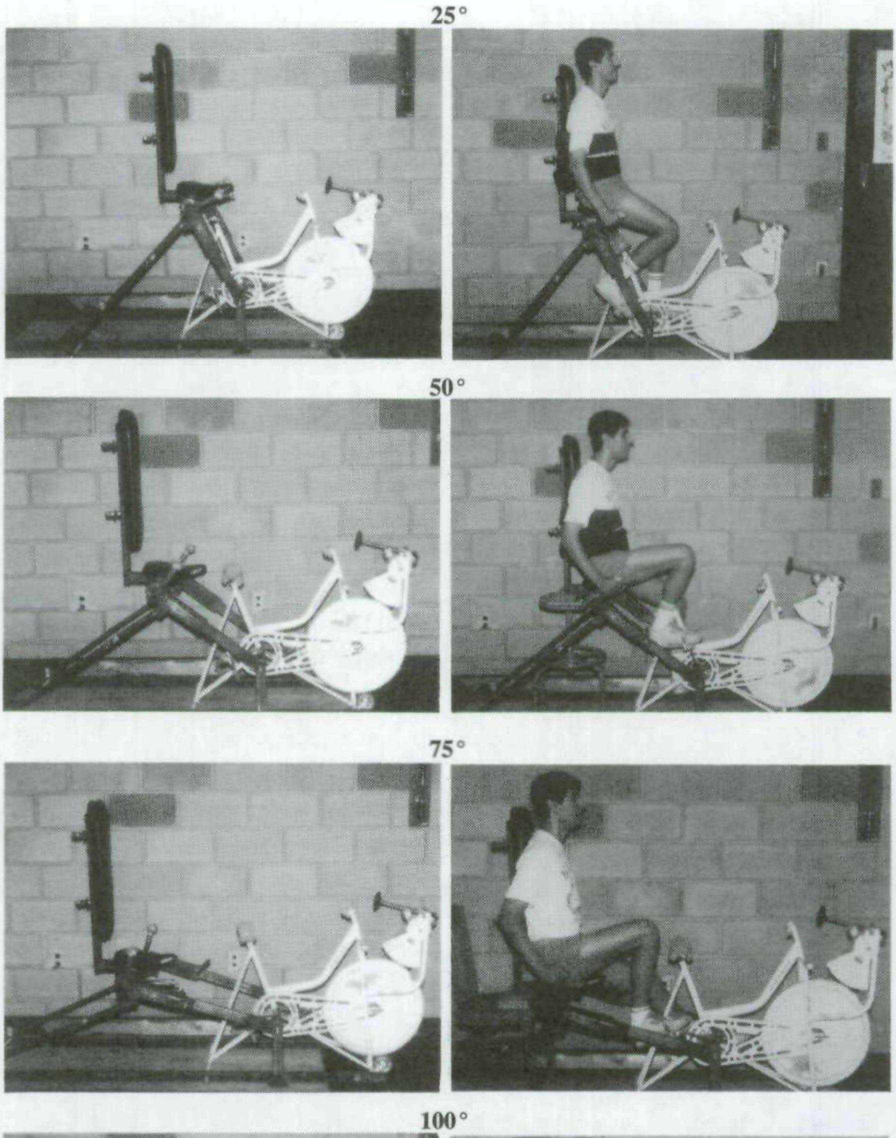

Figure 1 — Hip positions/configurations.

resulting power in kgm/min divided by 6.12 kpm/min converted the units of power to watts (or joules/second). Absolute peak power was then determined by the product of relative peak power and body mass. Anaerobic capacity was determined by the average number of flywheel revolutions for the six periods of successive 5 seconds in the 30-sec test. This mean relative power represents the maximal capacity to produce energy anaerobically (Lamb, 1984).

The total anaerobic capacity was then calculated by the product of the mean relative power and body mass. The fatigue index was calculated as a percentage of peak power by subtracting the lowest power (for the 5-sec ranges) from the peak power score, dividing by the peak power, and multiplying by 100 (Bar-Or, 1987).

Analysis

Repeated-measures MANOVA was used to determine significant differences in peak anaerobic power and anaerobic capacity with changes in hip position. In addition, post hoc tests (Dunnett) were used to determine the position and corresponding configuration which resulted in significantly greater peak anaerobic power and capacity. Finally, trend analysis was used to identify the function that best described the characteristics of the performance variables with changes in cycling position and configuration.

Results

The mean hip, knee, and ankle angles (minimum, maximum, average, and range of motion) for the four hip positions with changes in seat tube angles are presented in Table 1. There was a systematic decrease in the minimum, maximum, and average hip angles with changes in hip position from the 25 to the 100° position. Similar hip angle ranges of motion as well as mean knee angles with changes in hip positions suggest that the seat-to-pedal distance was controlled for. Therefore, differences in cycling performance can be attributed to changes in hip angle.

The mean peak anaerobic power (AP), anaerobic capacity (AC), anaerobic power and anaerobic capacity relative to each subject's body mass (AP/kg BM and AC/kg BM, respectively), and the fatigue index (FI) for the different body positions are presented in Table 2.

The mean AP and AP/kg BM of the four hip positions found in this investigation were within one standard deviation of most of the AP and AP/kg BM means reported in the literature (Table 3). The greater AP and AP/kg BM means of this investigation may be attributed to the use of a greater load (5.0 joules/rev/kg BM), since there is evidence that peak AP will increase with greater resistances (Patton, Murphy, & Frederick, 1985). The hip range of motion and knee angle (minimum, maximum, and range of motion) of the different hip positions were consistent with what has been reported in the literature.

For elite cyclists, Cavanagh and Sanderson (1986) reported the hip range of motion to be 43° and the knee angles (minimum, maximum, and range of motion) to be 69, 143, and 74°, respectively. This would suggest that the hip angle range of motion and knee angles controlled for in this investigation are very similar to that of a standard cycling position.

A repeated-measures MANOVA revealed the following significant differences ($p<.01$) with changes in hip position: AP with $F(3,39) = 13.6$; AC with $F(3,39) = 15.85$; AP/kg BM with $F(3,39) = 13.39$; and AC/kg BM with $F(3,39)$

Table 1

Hip, Knee, and Ankle Angles at Four Seat Tube Angles

		Seat tube angle (deg)			
		25	50	75	100
Hip (deg)					
Min.	*M*	93.7	79.7	54.4	37.9
	SD	4.21	5.31	6.92	5.40
Max.	*M*	135.3	120.4	96.7	79.8
	SD	4.65	6.90	4.81	3.53
Avg.	*M*	114.0	100.1	75.5	58.9
	SD	3.53	5.01	3.86	3.98
Range	*M*	41.9	40.7	42.4	42.6
	SD	6.90	7.17	9.09	5.77
Knee (deg)					
Min.	*M*	62.9	63.2	64.5	65.1
	SD	4.85	3.07	3.61	5.31
Max.	*M*	133.6	136.8	142.6	138.1
	SD	6.64	6.44	7.11	11.90
Avg.	*M*	98.2	100.0	103.6	101.6
	SD	5.36	4.45	4.38	8.21
Range	*M*	73.5	73.6	77.4	73.0
	SD	11.93	4.72	7.19	8.51
Ankle (deg)					
Min.	*M*	83.4	81.9	83.4	78.8
	SD	6.20	8.33	11.06	10.78
Max.	*M*	101.7	93.3	102.2	101.4
	SD	8.77	7.00	6.48	7.68
Avg.	*M*	92.5	89.6	92.8	90.1
	SD	6.65	6.57	7.19	7.93
Range	*M*	18.4	15.4	18.1	23.0
	SD	7.32	8.00	11.21	10.06

= 15.36. Post hoc tests (Dunnett) were used to compare the 75° hip position (also corresponding to the 75° hip angle configuration) with each of the other three positions. It was found that the AP, AC, AP/kg BM, and AC/kg BM in the 75° position/configuration was significantly greater than those in the 25 and 100° positions (114 and 59° hip angle configuration, respectively) ($p<.01$), but not significantly different from those in the 50° position (100° hip angle configuration). Based on trend analysis, a quadratic function ($p<.01$) was found to best describe the change in AP, AC, AP/kg BM, and AC/kg BM with changes in hip angles from 114 to 59° (Figure 2).

Table 2

Mean Values for Absolute and Relative Anaerobic Power and Capacity, With the Fatigue Index for Four Seat Tube Angles and Corresponding Hip Angles

		Seat tube angle (deg)			
		25	50	75	100
Hip angle (deg)		114.0	100.1	75.5	58.9
An. power (W)	*M*	739.2	800.1	821.2	763.1
	SD	134.2	126.8	122.9	111.9
An. capa. (W)	*M*	526.3	569.8	579.7	547.2
	SD	82.4	82.8	75.1	74.2
An. power/kg BM	*M*	10.55	11.43	11.73	10.91
(W/kg BM)	*SD*	1.38	1.17	1.03	1.04
An. capa./kg BM	*M*	7.53	8.14	8.29	7.84
(W/kg BM)	*SD*	.85	.66	.61	.73
Fatigue index (%)	*M*	49.4	48.8	49.6	47.9
	SD	9.63	4.23	7.16	5.54

Table 3

Peak Anaerobic Power Reported in Previous Studies Using the Bicycle Ergometer

				Peak anaerobic power	
Authors	*n*	Age (yrs)	Wt (kg)	(W)	(W/kg BM)
Ayalon, Inbar, & Bar-Or (1975)	15	19–21	71.9	461 (83)	6.4
Katch & Weltman (1979)	16	22.5	71.2	677 (23)	9.5
Bar-Or et al. (1980)	19	20–30	71.9	731 (75)	10.1
Crielaard & Pirnay (1981)	32	18.9	70.1	710 (58)	10.1 (1.2)
Nakamura, Mutoh, & Miyashita (1985)	26	21–28	69.4	927 (187)	3.4 (1.6)

Note. Standard deviations in parentheses.

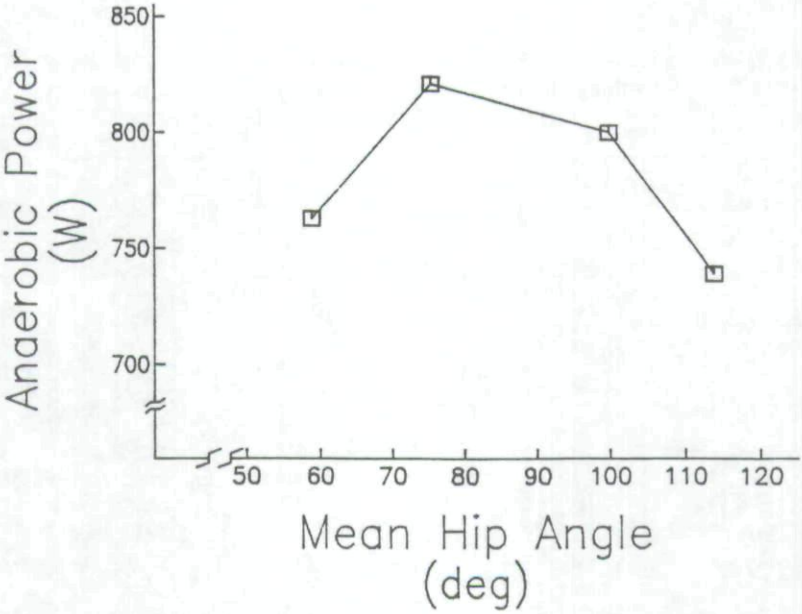

Figure 2 — Peak anaerobic power on the Wingate test with mean hip angles (averaged between minimum and maximum) for the four seat tube angles.

Discussion

The 75° position/configuration that resulted in the largest performance values for anaerobic power and anaerobic capacity is identical to the seat tube angle and hip angle reported in the literature that maximized aerobic work (Too, 1988, 1990a, 1990b). It is interesting to note that Hull and Gonzalez (1990), through optimization analysis, determined the optimal seat tube angle that would minimize the cost function involved in cycling to be 78.1, 75.8, and 73.3° for a short, average, and tall man, respectively. Hull and Gonzalez defined a short, average, and tall man to be 162.6 cm (5 ft 4 in.), 177.8 cm (5 ft 10 in.), and 193 cm (6 ft 4 in.) in height, respectively.

The results of this investigation indicate that there is a significant curvilinear trend in AP and AC with changes in hip position/configuration. This trend may be attributed to differences in minimum and maximum hip angle values with changes in hip position. Although there is a similar hip angle range of motion with changing hip position, the differences in minimum and maximum hip angle values would suggest that the development of force and production of power vary at different hip angles with changes in hip position. This is an explanation for differences in AP and AC with changes in hip position/configuration. This would also suggest some hip position/configuration, with an upright trunk orientation, which maximizes AP, AC, AP/kg BM, and AC/kg BM.

Verbal feedback from the subjects appear to support this curvilinear trend and performance differences. In the 25° hip position the subjects indicated that muscle fatigue was greatest in the quadriceps region, whereas it was greatest and localized in the gluteal area for the 100° hip position. However, in the 75° hip position the subjects reported muscular fatigue to be more generalized throughout the lower extremities. This would suggest that the 75° hip position and similar ones allow for a more equitable distribution of load over the various muscle groups involved.

The results of this investigation provide only limited information regarding the optimal seating position, configuration, and orientation that will maximize and optimize cycling performance. They do not provide direct information on how the various muscle moment arm lengths combine and interact with muscle length at different joint angles for single or multiple joint muscles.

The results also may not provide useful information to cyclists who pedal and compete on a traditional bicycle on which the only possible manipulations are in seat height, pedal crankarm length, and shifting the seat forward or backward on the seat post. Although cyclists can alter hip angles by a forward lean of the trunk, these manipulations are generally made to minimize aerodynamic drag rather than to maximize force and power production. Even if hip angles similar to those reported in this investigation can be reproduced on a standard bicycle, there is not enough information in the literature to predict how the change in trunk orientation with a standardized hip position will affect power production and cycling performance.

The information provided by this investigation would be more useful to those who design the next generation of human powered vehicles. Currently, human powered vehicles with an aerodynamic fairing are designed by engineers to minimize aerodynamic drag, often neglecting the human factors component. These vehicles are constructed to minimize the drag coefficient and cross-sectional area by constraining the cyclist to pedal in a given position, configuration, and/or orientation, which does not necessarily maximize force and power production. Although this investigation has determined that a certain hip position/angle will maximize anaerobic cycling performance, there are still many issues that need to be addressed.

One question is, why is cycling performance in one hip position greater than that in another position? Are these differences in performance due to changes in muscle length, moment arm length, joint angles, or other variables such as EMG patterns? Because subjects have reported that local muscle fatigue varies with changes in hip position, it may be that muscle activation and recruitment patterns have been altered with changes in hip position. It has not been determined whether the intensity, duration, and EMG patterns of a given muscle group will change (or how) with manipulations in hip position, or whether unfamiliar hip positions will affect the sequence and/or timing parameters of the different muscle groups involved in cycling.

Another question is, do changes in trunk orientation affect cycling performance, as determined by power production rather than minimizing aerodynamic drag, while controlling for hip position/configuration? In this investigation the trunk orientation was upright and perpendicular to the ground. Changing the trunk orientation will alter the lower limb orientation with respect to the line of gravity. Whether this change in trunk orientation will alter the lower limb weight contribution to the pedal, and how substantial or significant this contribution may be, is uncertain. If there is an effect or trend in cycling performance with a systematic manipulation in trunk orientation, will this trend be consistent with a different hip position/configuration or will there be an interaction effect?

One may also consider how the EMG patterns in cycling may change with changing trunk orientation. As an example, a cyclist cycling in a completely inverted trunk orientation would probably be more effective when pulling on the pedal toe-clips (and using the body weight to help with the pull) than when pushing against the pedal to overcome both the lower limb weight and cycling resistance. One may speculate that the force contribution and EMG patterns of the different muscle groups involved in an inverted cycling trunk orientation will be quite different than those of an upright trunk orientation. But how these patterns may change is unknown.

Other questions concern whether the optimal seat-to-pedal distance and/or pedal crank arm length for an upright seating position, as reported in the literature (Astrand, 1953; Carmichael, 1981; Goto, Toyoshima, & Hoshikawa, 1976; Gregor, Green, & Garhammer, 1981; Hamley & Thomas, 1967; Hull & Gonzalez, 1990; Inbar, Dotan, Trousil, & Dvir, 1983; Klimt & Voigt, 1974; Nordeen, 1976; Nordeen-Snyder, 1977; Shennum & deVries, 1976; Thomas, 1967a, 1967b, 1967c; Whitt, 1969), would remain the same with manipulations in hip position and/or trunk orientation, and how this would affect cycling performance.

Whether these variables of seat-to-pedal distance, crank arm length, hip position/configuration, and trunk orientation will interact to affect cycling performance, and whether these interactions and differences in cycling performance will be reflected in the EMG patterns, are questions that have yet to be answered.

To optimize cycling performance will require further research involving the human factors component and the incorporation of this information into the design and development of human powered vehicles. This would suggest the construction of a human powered vehicle that will not only minimize aerodynamic resistance but will also maximize force and power production by optimizing the seating position, configuration, and orientation of the cyclist.

Summary

A second-order function best describes the trend in anaerobic cycling performance with changes in hip position/configuration. This would imply that with the trunk in an upright orientation there is some hip position/angle that will maximize cycling performance as defined by anaerobic power and anaerobic capacity, and that an intermediate position (50–75°) produces the greatest power. The issues in this area require further research involving a series of investigations in which selected variables involving body position, configuration, and orientation are systematically manipulated.

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